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Technical Report

DOSE-ATTENUATION VARIATION WITH INCIDENT GAMMA-RAY ENERGY IN TWO-LEGGED CONCRETE AND STEEL DUCTS

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U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

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DOSE-ATTENUATION VARIATION WITH INCIDENT GAMMA-RAY ENERGY IN TWO-LEGGED CONCRETE AND STEEL DUCTS

Technical Report

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by

J. M. Chapman

ABSTRACT

Gamma-ray dose-attenuation factors were measured in concrete and steel ducts. For concrete, 3-foot-square and 11-inch-square ducts were used with Au^{198} (0.412 Mev), Cs^{137} (0.662 Mev), and Co^{60} (1.25 Mev) gamma-ray sources. For steel, an 11-inch-square duct was used with Cs^{137} and Co^{60} sources. Attenuation factors for given geometries were compared as a function of incident gamma-ray energy. The relative effectiveness of steel and concrete ducts of a given geometry was determined.

It was found that the attenuation factor decreases monotonically with increasing energy in concrete ducts. However, in the 11-inch steel duct the attenuation factor for the high-energy source (Co^{60}) was greater than for the low-energy source (Cs^{137}). In comparing the 11-inch concrete and 11-inch steel ducts, it was found that dose rates in the concrete duct were higher by a factor of about 2. Measured attenuation factors were compared with values obtained using a computer code based on the albedo concept. It was found that calculated attenuation factors agree to within ±30% of the measured attenuation factors.

The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.
This work sponsored by the Defense Atomic Support Agency.

INTRODUCTION

Dose rates were measured in 3-foot-square and 11-inch-square concrete ducts, using Au^{198} (0.412 Mev), Cs^{137} (0.662 Mev), and Co^{60} (1.25 Mev) gamma-ray sources and in an 11-inch-square steel duct, using Cs^{137} and Co^{60} gamma-ray sources. These dose rates were converted to attenuation factors so that the relative shielding effectiveness of concrete and steel ducts against gamma rays of different energies could be determined.

The attenuation factor, A_f, at some point in a duct is defined as the ratio between the dose rate at that point, D, and the dose rate in air at unit distance from the source, D_o, or $A_f = D/D_o$.

Measured attenuation factors can also be compared with values calculated with a computer program.[1] This program calculates attenuation factors in two-legged ducts using the albedo concept. Results from this program were compared with measurements performed in concrete ducts by several different experimenters. These experiments covered a wide range of duct sizes and incident gamma-ray energies. Values of attenuation factors calculated with the computer program were normally within ±30% of the experimental values. The only exception was in comparison with Terrell's[2] concrete-duct studies using an Au^{198} source, for which calculated values were high by a factor of 2.2.

Terrell's were the only data in which a relationship could be found between the attenuation effectiveness of ducts and gamma-ray energy. Figure 1 was constructed from Terrell's data and shows a peculiar behavior. Instead of the experimental attenuation factors decreasing monotonically with increasing gamma-ray energy, as do the calculated values, the experimental attenuation factor for Au^{198} is less than that for Cs^{137}. This anomalous behavior is not shown by the concrete-duct measurements discussed in this report under Results.

The anomalous behavior of the attenuation factor versus gamma-ray energy curve, and the need for more low-energy data for comparison with the computer program, prompted the present experiments with the concrete ducts. The measurements in the steel duct constitute this Laboratory's first step in extending the knowledge of duct streaming to materials other than concrete. Albedo values for iron were generated by the Monte Carlo method, and the computer programs of Reference 1 were used to calculate A_f for the 11-inch steel duct for comparison with experimental results.

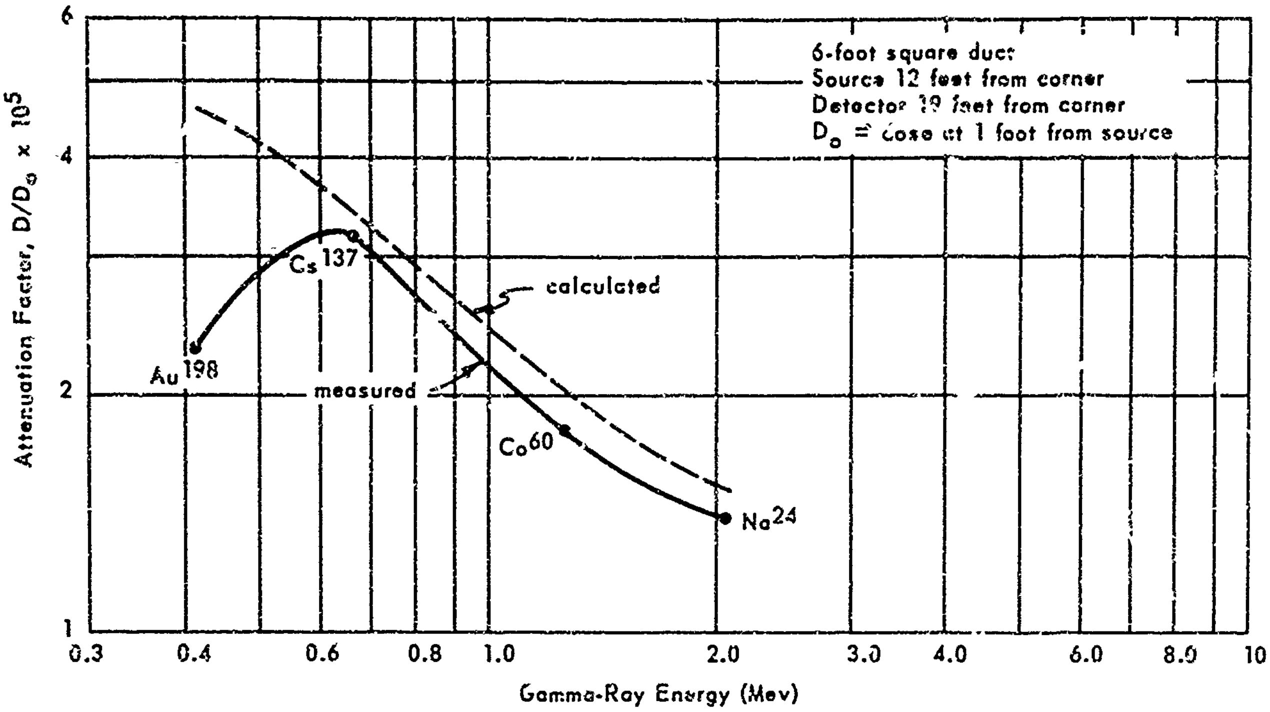

Figure 1. Variation of dose attenuation with energy for a given geometry in a 6-foot concrete duct.

ALBEDO VALUES FOR IRON AND CONCRETE

The computer calculations are based on the albedo concept. The dose rate, D, from a scattering area, A (Figure 2), is given by

$$D = \frac{D_o \alpha(E_o, \theta_o, \theta, \varphi) A \cos\theta_o}{r_1^2 r_2^2}$$

where $\alpha(E_o, \theta_o, \theta, \varphi)$ = the differential dose albedo

A = the area of the scattering surface

D_o = the dose rate at one unit length from the source

E_o = the initial energy of the gamma rays

Values for $\alpha(E_o, \theta_o, \theta, \varphi)$ have been calculated for various energies and entrance and exit angles by the Monte Carlo method. Technical Operations, Incorporated[3] performed calculations for concrete using 5,000 case histories for each energy and entrance angle, and NCEL performed calculations for both concrete and iron using 30,000 case histories.[4]

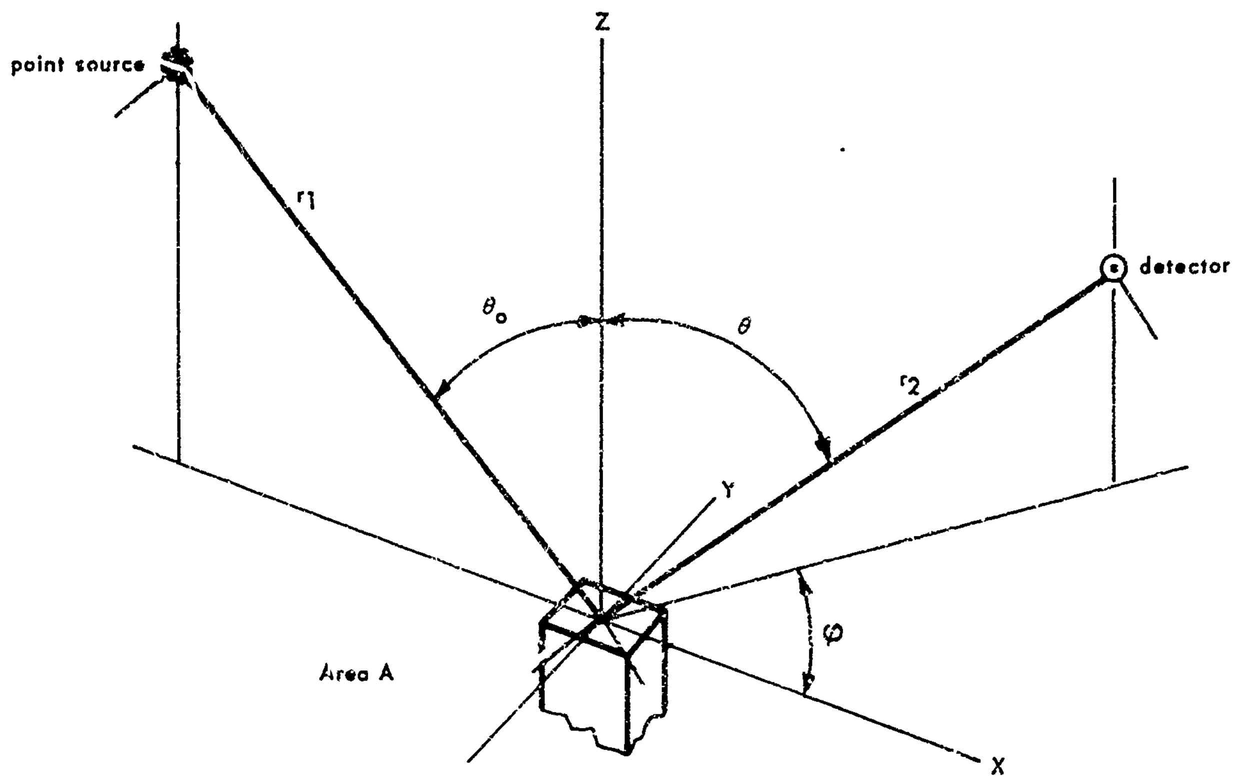

Figure 2. Scattering of gamma-rays from surface.

The equation developed by Chilton and Huddleston[5] to express the albedo for a given energy is

$$\alpha(E_o, \theta_o, \theta, \varphi) = \frac{C(E_o)\,K(\theta_s)\,10^{26} + C'(E_o)}{1 + \dfrac{\cos\theta_o}{\cos\theta}}$$

where $C(E_o)$ and $C'(E_o)$ are constants for a given energy, $K(\theta_s)$ is the Klein-Nishina differential energy-scattering coefficient for the angle, θ_s, through which the radiation is scattered. $\cos\theta_s$ is given by

$$\cos\theta_s = \sin\theta_o \sin\theta \cos\varphi - \cos\theta_o \cos\theta$$

The values of $C(E_o)$ and $C'(E_o)$ were found by a least-squares fit of the Monte Carlo data from the 30,000 case histories and are given in Table I for concrete and iron. These values are plotted in Figure 3 for concrete and Figure 4 for iron. For computation on the computer, the curves of Figures 3 and 4 were fitted by the equations:

Concrete

$$C = 0.0561\, E_o^{0.574} \qquad 0.2 \le E_o \le 4.0 \text{ Mev}$$

$$C = 0.0785\, E_o^{0.327} \qquad 4.0 < E_o \le 10.0 \text{ Mev}$$

$$C' = 0.0122\, E_o^{-0.683} \qquad 0.2 \le E_o \le 1.76 \text{ Mev}$$

$$C' = 0.00862\, E_o^{-0.0795} \qquad 1.76 < E_o \le 10.0 \text{ Mev}$$

Iron

$$C = 0.590\, E_o^{0.586} \qquad 0.175 \le E_o \le 2.0 \text{ Mev}$$

$$C' = \exp[-5.32 - 1.39 \ln E_o - 1.06 (\ln E_o)^2] \qquad 0.175 \le E_o \le 0.412$$

$$C' = 0.073 \qquad 0.412 < E_o \le 4.0 \text{ Mev}$$

The energy-absorption coefficients for iron are also necessary for use in the computer code. Values used are from Reference 6. These values are plotted as relaxation lengths (R_L) in Figure 5. For the computer, the points of Figure 5 were fit by the equations:

$$R_L = \exp[-0.676 - 2.25 \ln E - 1.13 (\ln E)^2] \qquad 0.1 \le E \le 0.336 \text{ Mev}$$

$$R_L = 1.95\, E^{0.205} \qquad 0.336 < E \le 4.0 \text{ Mev}$$

EXPERIMENTAL MEASUREMENTS

Dosimeter measurements were made in a 3-foot-square concrete duct (Figures 6 and 7), an 11-inch concrete duct (Figure 8), and an 11-inch steel duct (Figure 9). The 3-foot concrete duct had 4-inch-thick walls and was covered with approximately 2 feet of sand. The legs were each 15 feet long. The 11-inch concrete duct was made of concrete blocks and had walls from 6 to 15 inches thick. The legs were 51 inches long. The 11-inch steel duct was made of ASTM standard A7 steel, about 0.25% carbon, 0.5% manganese, 0.04% phosphorous, and 0.05% sulfur. The walls were 3 inches thick, and the legs were 50 inches long. The duct was covered with at least 3 feet of sand on each side.

Table I. The Parameters C and C' for Concrete and Iron

E (Mev)	Concrete		Iron	
	C	C'	C	C'
0.175	—	—	0.0190 ± 0.0007	0.0022 ± 0.0013
0.200	0.0224 ± 0.0010	0.0366 ± 0.0017	0.0226 ± 0.0007	0.0030 ± 0.0012
0.279	—	—	0.0280 ± 0.0007	0.0051 ± 0.0009
0.412	0.0344 ± 0.0009	0.0218 ± 0.0008	0.0358 ± 0.0008	0.0073 ± 0.0007
0.500	0.0364 ± 0.0009	0.0200 ± 0.0007	—	—
0.662	0.0435 ± 0.0010	0.0161 ± 0.0006	0.0469 ± 0.0009	0.0073 ± 0.0005
1.00	0.0557 ± 0.0011	0.0117 ± 0.0004	0.0597 ± 0.0011	0.0061 ± 0.0004
1.25	0.0665 ± 0.0013	0.0107 ± 0.0004	0.0664 ± 0.0013	0.0090 ± 0.0004
2.00	0.0846 ± 0.0016	0.00814 ± 0.00026	0.0883 ± 0.0016	0.0066 ± 0.0002
4.00	0.1222 ± 0.0029	0.00761 ± 0.00020	0.0880 ± 0.0023	0.0079 ± 0.0002
6.00	0.1439 ± 0.0041	0.00767 ± 0.00018	—	—
10.00	0.1653 ± 0.0056	0.00708 ± 0.00014	—	—

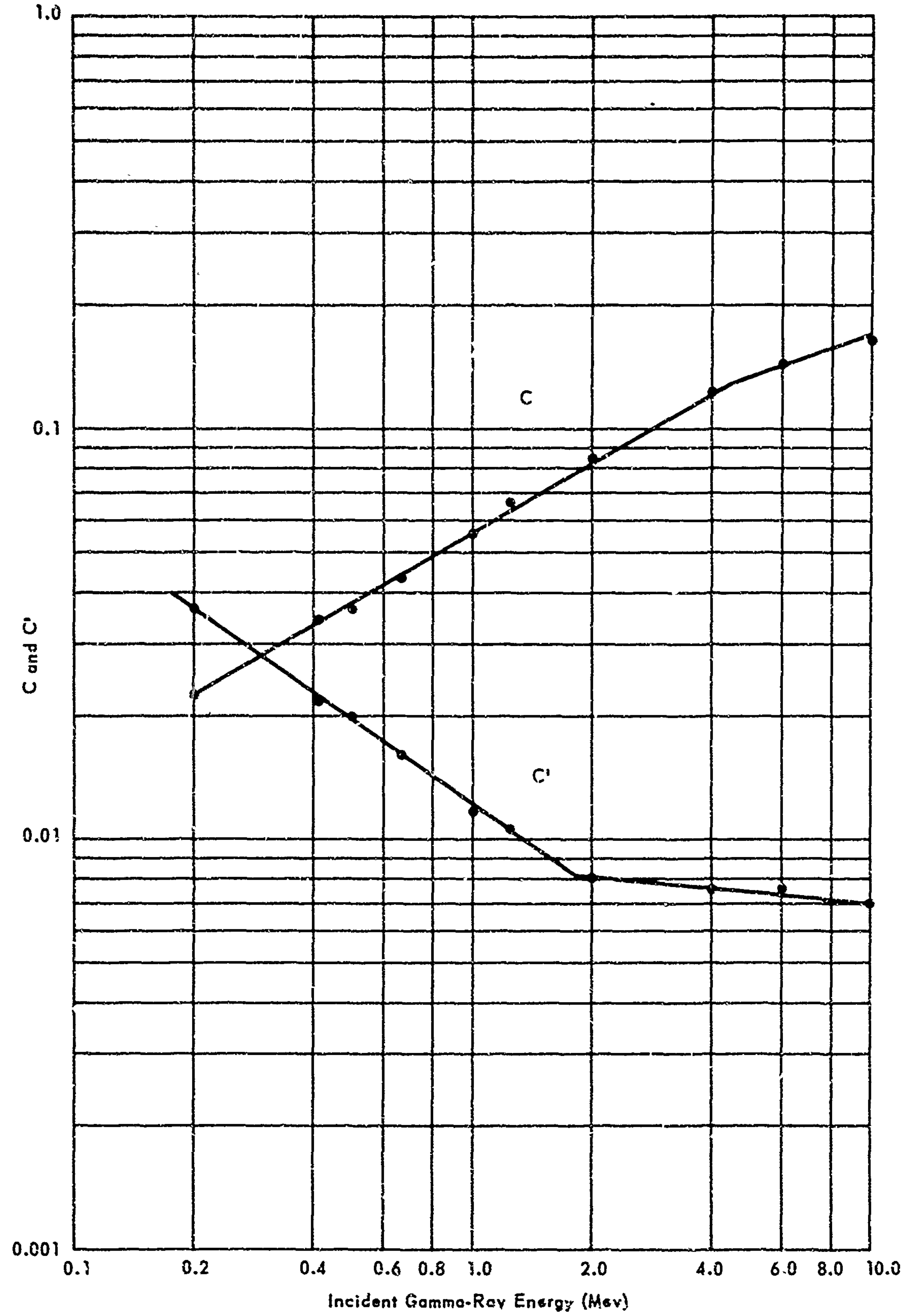

Figure 3. Parameters C and C' versus energy for concrete.

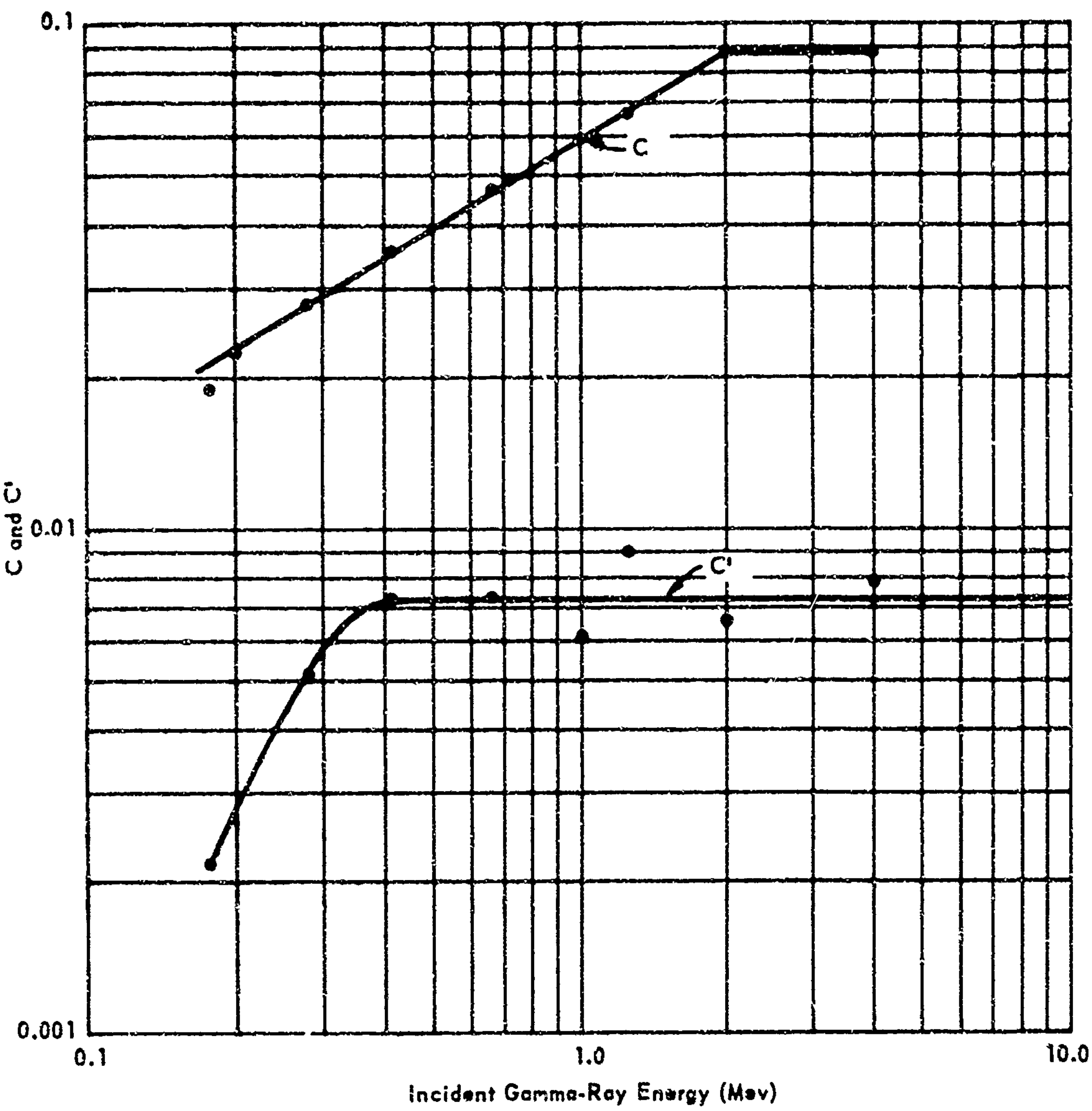

Figure 4. Parameters C and C' versus energy for iron.

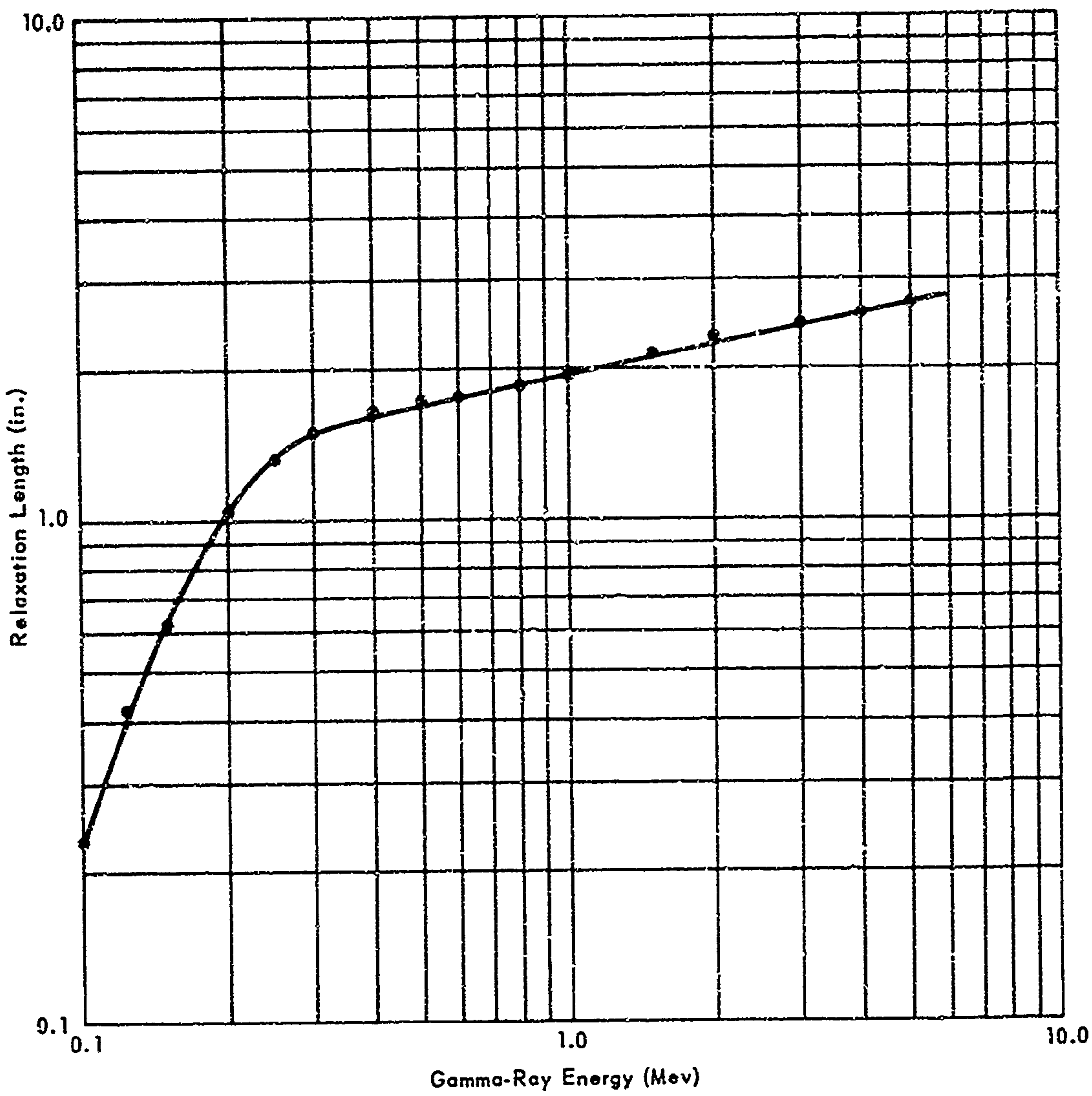

Figure 5. Relaxation length versus gamma-ray energy for iron.

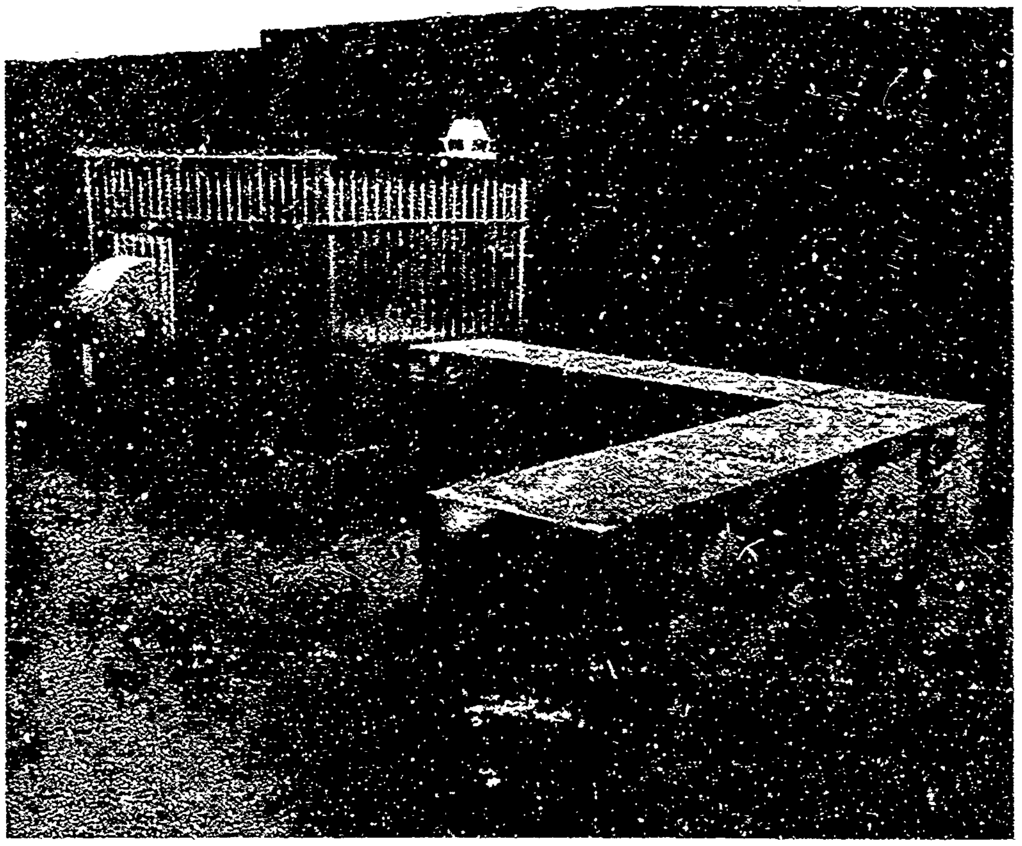

Figure 6. The 3-foot duct, adjacent to the neutron-generator room, shown without shielding.

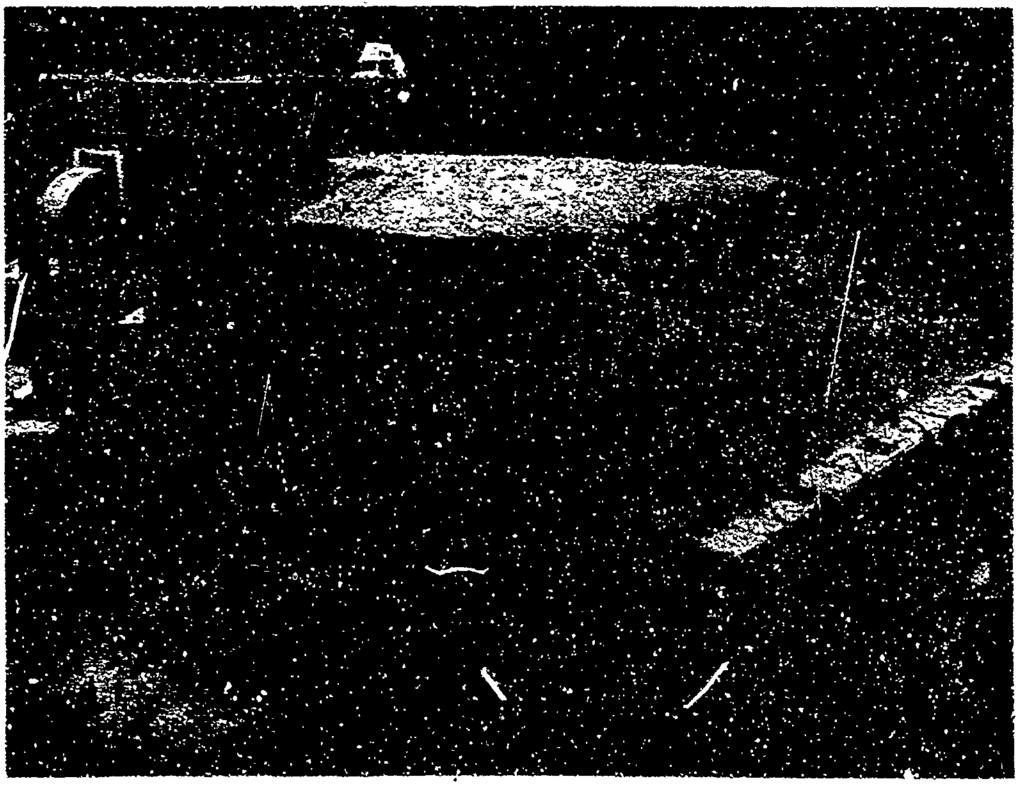

Figure 7. The 3-foot duct shielded with sand.

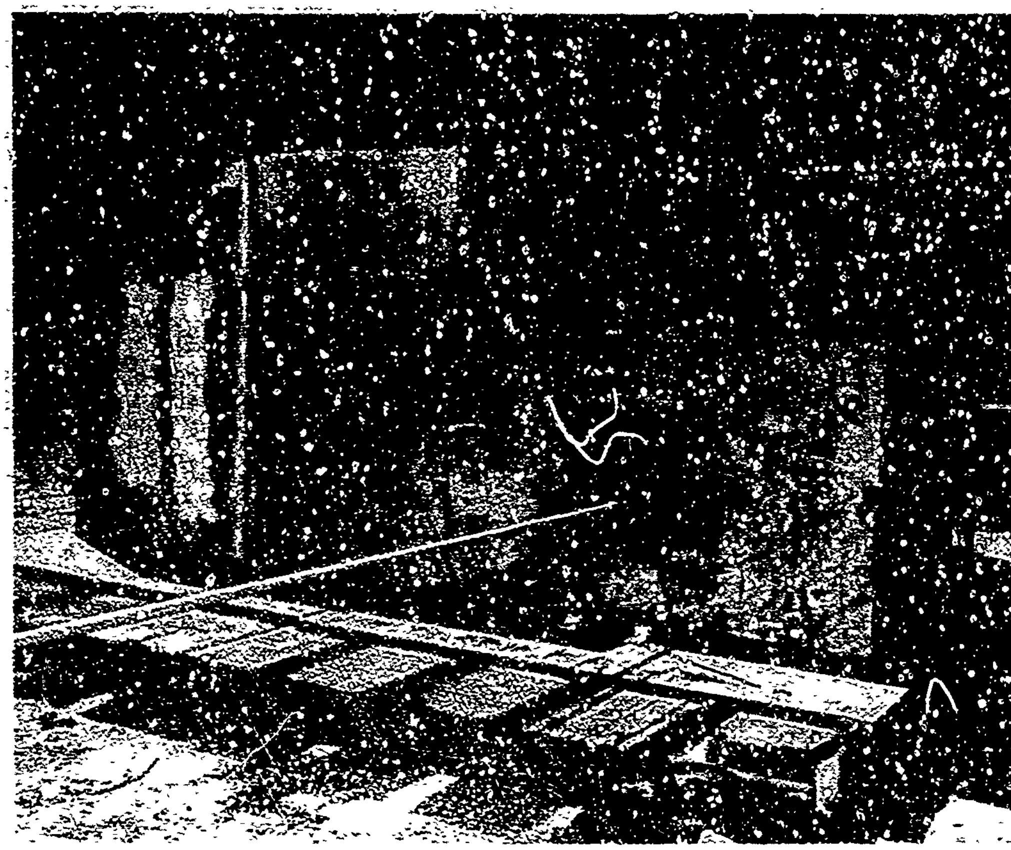

Figure 8. The 11-inch duct. The source is held in the wooden cup attached to the end of the aluminum tube.

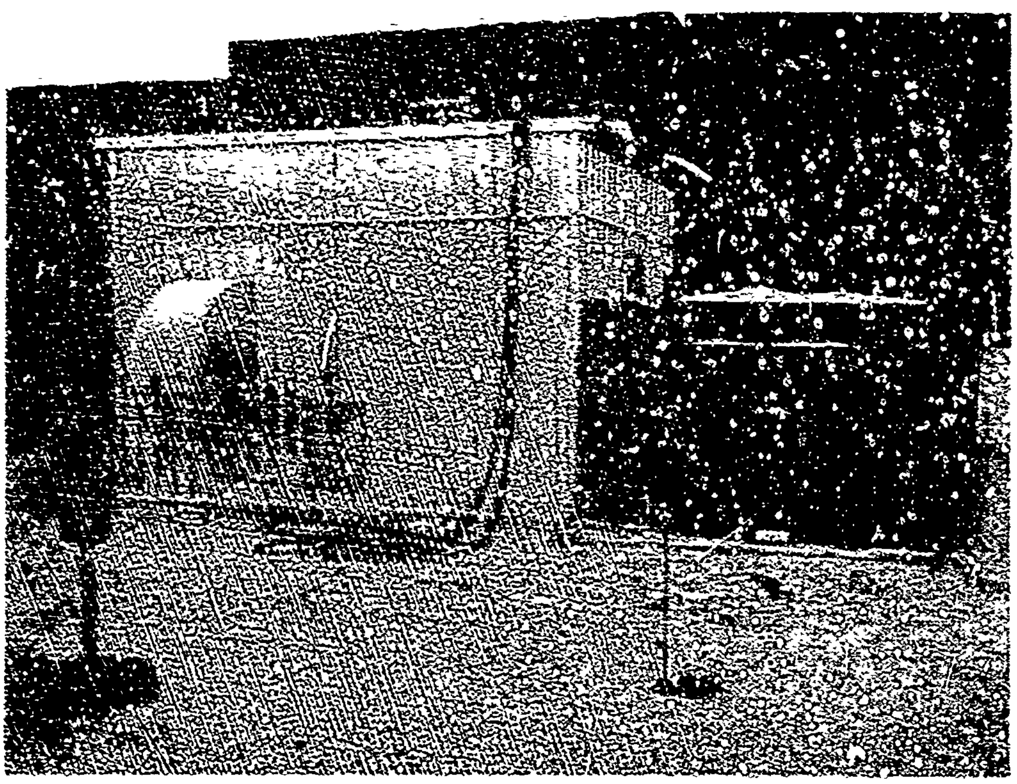

Figure 9. The 11-inch steel duct, covered with approximately 3 feet of sand.

The dosimeters used were the 1-r, 100-mr, and 10-mr chambers from a Landsverk L-64 dosimeter set. Those readings for which the dosimeter was in direct view of the source were taken with a 3/8-inch bakelite sleeve around the dosimeter, as recommended by the manufacturer. The variation observed for an individual dosimeter was about 2%, but the variation from dosimeter to dosimeter was about 10%. The measurements were therefore considered accurate to within ±10%.

Source strengths were determined by measuring the dose rates from 3 feet to 8 feet from the source. For these measurements, the source and dosimeter were 6-1/2 feet from the ground, so build-up was expected to be small. Dose rate to source strength conversions were made, using the point source gamma-ray dose-rate constant Γ (r/hr from 1 millicurie at 1 centimeter), given in Table 1B of Reference 7. These are 12.8 for Co^{60}, 3.2 for Cs^{137}, and 2.35 for Au^{198}.

Gamma-ray spectra of the sources were measured with a collimated 3 x 3-inch NaI(Tl) crystal and a multichannel analyzer. These spectra showed no extraneous gamma rays. Source strengths calculated from the spectra agreed with those measured by dosimeters to within ±10%.

The Co^{60} and Cs^{137} measurements for the 3-foot concrete duct were taken from previous work.[8] At the time of that work, the source strengths were 2.4 curies for Co^{60} and 0.79 curies for Cs^{137} (erroneously reported as 0.60 curies). In the measurements of the 11-inch concrete duct discussed here, the source strengths were 2.1 curies for Co^{60} and 0.78 curies for Cs^{137}. The length of time required to perform the present experiments necessitated having two Au^{198} sources. The first was 11.0 curies, and the second was 15.5 curies. All readings taken with the two Au^{198} sources were normalized to their original strengths, using a half-life of 2.7 days.

During the measurements of the 11-inch steel duct, the source strengths were 2.00 curies for Co^{60} and 0.77 curies for Cs^{137}.

All duct dosimeter measurements were taken with the source and dosimeter on the centerline of the duct. For the 3-foot duct, the source was placed in a lucite cup and suspended from a thin metal stand. The dosimeters were hung from the ceiling of the duct with string and tape. Placement of the source and dosimeter was accurate to within 1/2 inch. For the 11-inch duct, the source was placed in a thin wooden cup on the end of a thin aluminum tube, and the tube was inserted into the duct. Dosimeters were held on a thin wood grid which could be accurately placed in the duct. Placement of source and dosimeter in the 11-inch duct was accurate to within 1/10 inch.

RESULTS

Measured dose rates, D, versus centerline distance, C_L, are listed in Tables II-IV for the 3-foot concrete duct with L_1 = 6 feet,* the 3-foot concrete duct with L_1 = 7-1/2 feet, and the 11-inch concrete duct with L_1 = 45.4 inches. Measured dose rates for the 11-inch steel duct with L_1 = 45.4 inches are listed in Table V. In these tables, the dose rates are converted to attenuation factors and compared to calculated attenuation factors.

As can be seen from Tables II-IV, the attenuation factors show a monotonic decrease with increasing energy for concrete. This is seen better in Figure 10, which shows measured and calculated attenuation factors versus energy for three given duct geometries. However, in the 11-inch steel duct the experimental attenuation factors for the higher energy (Co^{60}) are greater than those for the lower energy (Cs^{137}). This is a surprising result that is believed to be a true representation, as the 10 to 40% difference between these attenuation factors is well outside the experimental error.

From Table V it can be seen that the computer program, which gave good results for concrete ducts (normally within ±30% of experimental values), also gives good results for steel ducts. The computer values of attenuation factors, however, are monotonically decreasing with increasing energy. This indicates that if the oddity in the experimental results is real, it is due to some effect not considered in the calculations.

The attenuation effectiveness of steel and concrete ducts can be compared from Tables IV and V. Dose rates are higher in the concrete duct by a factor of about 2.1 for Cs^{137} and about 1.6 for Co^{60}. Higher dose rates for concrete ducts would be expected. This is because for iron there would be less backscattering, due to the higher-photoelectric-effect cross section of iron and less corner-lip penetration and inscatter, due to the larger energy-absorption coefficient of iron.

FINDINGS

A computer program[1] for calculating gamma-ray dose-attenuation factors in two-legged concrete ducts has generally given good agreement with experiment. An exception was the experimental results obtained with gamma rays from Au^{198},[2] which were in poor agreement with predictions from the computer code. The present measurements in concrete ducts using Au^{198}, Cs^{137}, and Co^{60} gamma-ray sources in three different duct configurations show good agreement between experiment and theory and no anomalous behavior for Au^{198}.

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* L_1 is the distance from the source to the center of the corner.

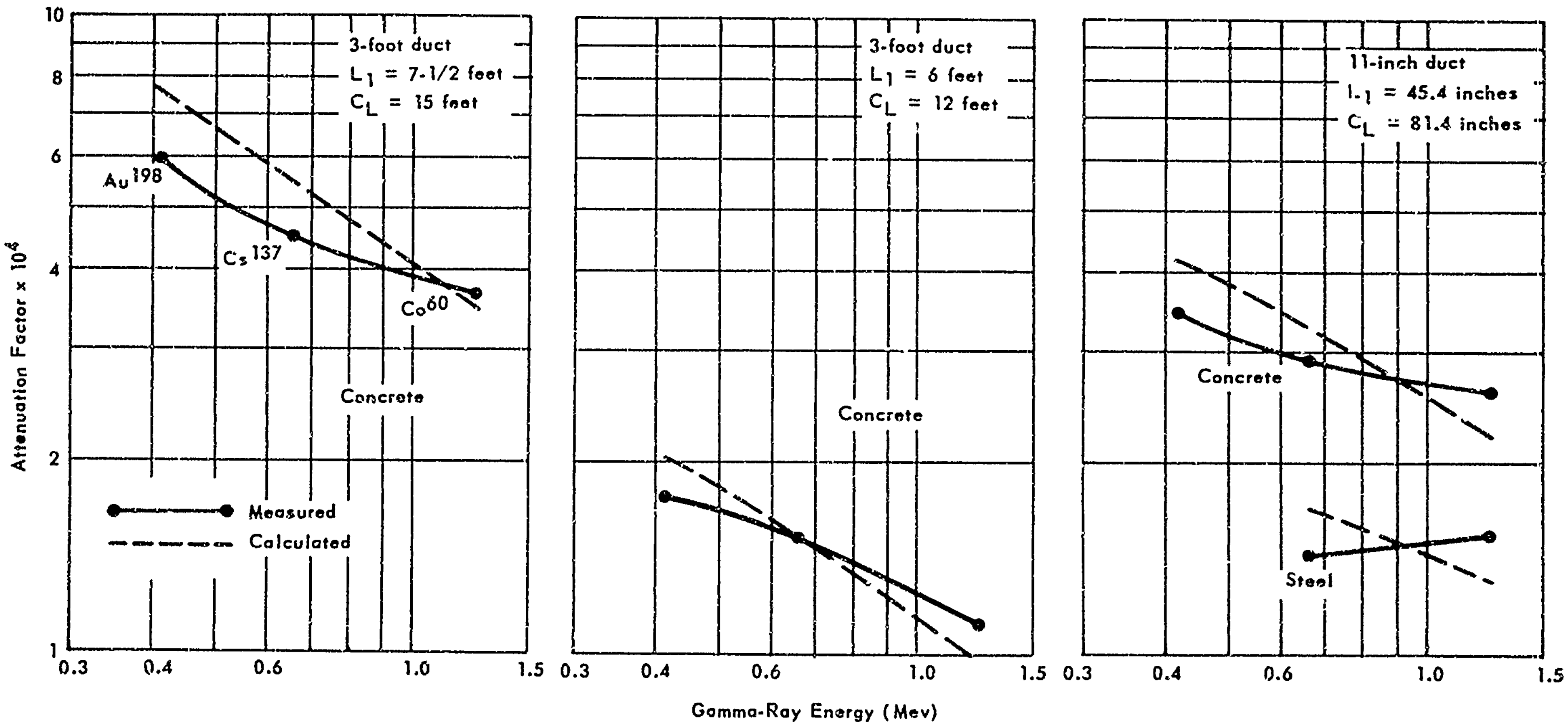

Figure 10. Variation of measured and calculated attenuation coefficients with energy for three given duct geometries.

Table II. Measured Dose Rates and Attenuation Factors, and Calculated Attenuation Factors in the 3-Foot Concrete Duct (L_1 = 6 Feet)1/

C_L (ft)	2.4-Curie Co^{60} ($D_o = 3.31 \times 10^4$ mr/hr)				0.79-Curie Cs^{137} (D_o = 2,725 mr/hr)				15.5-Curie Au^{198} ($D_o = 3.93 \times 10^4$ mr/hr)			
	D (mr/hr)	$A_f \times 10^4$		Diff. (%)	D (mr/hr)	$A_f \times 10^4$		Diff. (%)	D (mr/hr)	$A_f \times 10^4$		Diff. (%)
		Meas.	Calc.			Meas.	Calc.			Meas.	Calc.	
2	9,600	—	—	—	—	—	—	—	—	—	—	—
3	—	—	—	—	347	—	—	—	—	—	—	—
4	2,670	—	—	—	213	—	—	—	3,450	—	—	—
5	—	—	—	—	138	—	—	—	—	—	—	—
6	1,250	—	—	—	100	—	—	—	1,532	—	—	—
9	95.0	—	—	—	7.60	—	—	—	139	—	—	—
10	37.8	—	—	—	3.68	—	—	—	—	—	—	—
11	20.0	6.04	5.95	-1	2.03	7.45	9.36	+26	37.6	9.57	12.7	+33
12	12.1	3.66	3.43	-6	1.22	4.48	5.41	+21	23.3	5.93	7.37	+24
13	7.82	2.36	2.19	-7	0.841	3.09	3.46	+12	15.6	3.97	4.69	+18
14	—	—	—	—	0.601	2.21	—	—	11.1	2.83	3.24	+14
15	3.94	1.19	1.08	-9	0.450	1.65	1.70	+3	—	—	—	—

1/ $A_f = D/D_o$; D_o is the dose rate at 1 foot from the source; percentage of difference = (calculated - measured/measured) 100

Table III. Measured Dose Rates and Attenuation Factors, and Calculated Attenuation Factors in the 3-Foot Concrete Duct (L_1 = 7-1/2 Feet)

(See footnote on Table II)

C_L (ft)	2.4-Curie Co^{60} ($D_o = 3.31 \times 10^4$ mr/hr)				0.79-Curie Cs^{137} (D_o = 2,725 mr/hr)				11.0-Curie Au^{198} ($D_o = 2.79 \times 10^4$ mr/hr)			
	D (mr/hr)	$A_f \times 10^4$		Diff. (%)	D (mr/hr)	$A_f \times 10^4$		Diff. (%)	D (mr/hr)	$A_f \times 10^4$		Diff. (%)
		Meas.	Calc.			Meas.	Calc.			Meas.	Calc.	
3-1/2	3,555	—	—	—	276	—	—	—	3,250	—	—	—
4-1/2	—	—	—	—	—	—	—	—	1,950	—	—	—
5-1/2	1,508	—	—	—	122	—	—	—	1,350	—	—	—
7-1/2	835	—	—	—	68.5	—	—	—	725	—	—	—
9-1/2	—	—	—	—	—	—	—	—	183	—	—	—
10-1/2	50.6	—	—	—	4.05	—	—	—	52.4	—	—	—
11-1/2	20.8	—	—	—	1.97	—	—	—	25.5	—	—	—
12-1/2	11.4	3.44	3.05	-11	1.10	4.04	4.79	+19	14.5	5.20	6.47	+24
13-1/2	6.93	2.09	1.79	-14	0.690	2.53	2.83	+12	8.96	3.21	3.81	+19
15	3.68	1.11	0.962	-13	0.412	1.51	1.51	0	4.93	1.77	2.03	+15
16	—	—	—	—	—	—	—	—	3.59	1.29	1.45	+12

Table IV. Measured Dose Rates and Attenuation Factors, and Calculated Attenuation Factors in the 11-Inch Concrete Duct (L_1 = 45.4 Inches)

(See footnote on Table II)

C_L (in.)	2.1-Curie Co^{60} (D_o = 2.90 x 10^4 mr/hr)				0.78-Curie Cs^{137} (D_o = 2,690 mr/hr)				15.5-Curie Au^{198} (D_o = 3.93 x 10^4 mr/hr)			
	D (mr/hr)	$A_f \times 10^4$		Diff. (%)	D (mr/hr)	$A_f \times 10^4$		Diff. (%)	D (mr/hr)	$A_f \times 10^4$		Diff. (%)
		Meas.	Calc.			Meas.	Calc.			Meas.	Calc.	
36.4	—	—	—	—	435	—	—	—	6,600	—	—	—
40.9	—	—	—	—	349	—	—	—	—	—	—	—
45.4	3,160	—	—	—	279	—	—	—	3,900	—	—	—
58.9	—	—	—	—	—	—	—	—	170	—	—	—
63.4	56.5	—	—	—	4.90	—	—	—	85.2	—	—	—
67.9	29.7	10.2	8.68	-15	2.73	10.1	12.9	+28	46.7	11.9	16.7	+40
72.4	17.0	5.86	4.99	-15	1.66	6.17	7.44	+21	29.3	7.46	9.62	+29
76.9	10.6	3.65	3.19	-13	1.13	4.20	4.75	+13	19.0	4.84	6.10	+26
81.4	7.50	2.59	2.18	-16	0.782	2.90	3.23	1	13.5	3.44	4.13	+20

Table V. Measured Dose Rates and Attenuation Factors, and Calculated Attenuation Factors in the 11-Inch Steel Duct (L_1 = 45.4 Inches)

(See footnote on Table II)

C_L (in.)	2.00-Curie Co^{60} ($D_o = 2.76 \times 10^4$ mr/hr)				0.77-Curie Cs^{137} (D_o = 2,656 mr/hr)			
	D (mr/hr)	$A_f \times 10^4$		Diff. (%)	D (mr/hr)	$A_f \times 10^4$		Diff. (%)
		Meas.	Calc.			Meas.	Calc.	
22.9	9,988	—	—	—	943	—	—	—
27.4	6,800	—	—	—	676	—	—	—
31.9	—	—	—	—	508	—	—	—
40.9	3,230	—	—	—	309	—	—	—
45.4	2,767	—	—	—	250	—	—	—
58.9	—	—	—	—	4.62	—	—	—
63.4	30.5	—	—	—	2.19	—	—	—
67.9	17.3	6.27	4.19	-33	1.22	4.59	5.49	+20
72.4	10.2	3.70	2.65	-18	0.778	2.93	3.46	+18
76.9	6.33	2.29	1.80	-21	0.513	1.93	2.35	+22
81.4	4.25	1.54	1.29	-16	0.376	1.42	1.68	+18
86.9	2.86	1.04	0.959	-8	—	—	—	—

Measurements were also made in a steel duct using Cs^{137} and Co^{60} gamma-ray sources, and the computer program, using the backscattering and attenuation parameters for iron, was used to obtain calculated values of attenuation factors. Good agreement between calculated and experimental values was obtained for the steel duct. An oddity in the measurements in the steel duct, however, was that the experimental attenuation factors for Cs^{137} are less than those for Co^{60}. This oddity is unexplained and does not appear in the calculated attenuation factors.

In comparing the effectiveness of concrete and steel ducts in attenuating gamma radiation, it was found that dose rates in the second leg of a concrete duct were higher than in a steel duct by a factor of 2.1 for Cs^{137} and a factor of 1.6 for Co^{60}.

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8. U. S. Naval Civil Engineering Laboratory Technical Report R-325: Gamma-ray dose rates and energy spectra in a 3-foot square duct, by J. M. Chapman, Port Hueneme, Calif., Oct. 1964.

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Gamma-ray dose-attenuation factors were measured in concrete and steel ducts. For concrete, 3-foot-square and 11-inch-square ducts were used with Au^{198} (0.412 Mev), Cs^{137} (0.662 Mev), and Co^{60} (1.25 Mev) gamma-ray sources. Attenuation factors for given geometries were compared as a function of incident gamma-ray energy. The relative effectiveness of steel and concrete ducts of a given geometry was determined.

It was found that the attenuation factor decreases monotonically with increasing energy in concrete ducts. However, in the 11-inch steel duct the attenuation factor for the high-energy source (Co^{60}) was greater than for the low-energy source (Cs^{137}). In comparing the 11-inch concrete and 11-inch steel ducts, it was found that dose rates in the concrete duct were higher by a factor of about 2. Measured attenuation factors were compared with values obtained using a computer code based on the albedo concept. It was found that calculated attenuation factors agree to within ±30% of the measured attenuation factors.

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